

Optimization of Mechanical Properties of Friction Stir Spot Welded Joints for Dissimilar Aluminum Alloys (AA2024-T3 and AA 5754-H114)

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Abstract In this work, friction stir spot welding (FSSW) was performed for dissimilar aluminum alloys (AA2024-T3 and AA5754-H114) sheets of 2 mm thick at different tool rotational speeds (800, 1000 and 1250 rpm), plunging times (30, 60 and 90 s) and tool pin profile or geometry (threaded cylindrical with flute, tapered cylindrical and straight cylindrical). Process parameters were optimized by using Taguchi technique and depending on design of experiment (DOE), and data analysis based on the Taguchi method is performed by utilizing the Minitab 17 to estimate the significant factors of the FSSW and main effects using few experimental tests only. It was found that maximum shear force was (2860 N) obtained at best welding process parameters: 800 rpm of rotation speed, 60 s of plunging time and taper cylindrical pin which are obtained from the DOE. Pareto chart of the standardized effects of tensile shear results showed that the pin profile was the most effective parameter than other welding parameters (rotation speed and plunging time). Also it was found that the contribution percentage was 61.5 % for pin profile followed by tool rotation speed 20.1 % and plunging time 18.4 %.

Keywords Friction stir spot welding · Shear force · Dissimilar Al-alloys · Taguchi technique

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1 Introduction

Friction stir welding (FSW) was developed by TWI in 1991 [1]. It has been widely used in the aerospace, shipbuilding, automobile industries and in many applications because of many of its advantages over the conventional welding techniques, some of which include very low distortion, no fumes, porosity or spatter, no consumables (no filler wire), no special surface treatment and no shielding gas requirements [2]. Friction stir spot welding (FSSW) is a very useful variant of the conventional friction stir welding (FSW), which shows great potential to be a replacement of single-point joining processes like resistance spot welding and riveting, and it has wider applications in aerospace, aviation and automobile fields [3,4]. A number of studies have been conducted on friction stir spot welding (FSSW) between similar and dissimilar aluminum alloys and with other metals over the years as follows:

Merzoug et al. [5] conducted experiments of friction stir spot welding on AA6060-T5 using a tool steel of type X210 and the rotational speed in range from 1000 to 2000 rpm and tool feed 16–25 mm/min. They found that the tensile shear force was 5 kN at using 16 mm/min and 1000 rpm compared to 1.98 kN for 25 mm/min and 2000 rpm. The microhardness reaches maximum value they moved away from the nugget zone. Aval et al. [6] investigated the microstructures and mechanical properties in dissimilar friction stir welding of AA5086-O and AA6061-T6 using thermomechanical model and experimental observations. They found that the hardness in AA5086 side mainly depends on recrystallization and generation of fine grains in the weld nugget, whereas hardness in the AA6061 side varies with the size, volume fraction and distribution of precipitates in the weld line and adjacent heat-affected zone as well as the aging period after welding.



Table 1 Chemical composition of Al-alloys AA2024T3 and AA5754-H114

Element wt%	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	V	Other	Al
AA5457-H114	0.005	0.280	0.038	0.358	2.97	0.046	0.005	0.016	0.015	0.013	0.0327	Bal.
AA2024-T3	0.126	0.280	4.37	0.593	1.27	0.0013	0.0099	0.166	0.0167	0.01	–	Bal.

Table 2 Mechanical properties of Al-alloys used in this study

Alloys	Yield strength (MPa)	Tensile strength (MPa)	Elongation %
AA2024-T3	345	450	22
AA5754-H114	191	248	18

Krishna et al. [7] used the Taguchi experimental design technique to determine the optimum friction stir welding parameters for dissimilar Al2024-T6 and Al6351-T6 alloys. Effect of FSW process parameters such as tool rotation speed, welding speed and axial force on tensile strength was evaluated. A mathematical model based on nonlinear regression was developed to establish relation between welding parameters and tensile strength. From ANOVA, it is found that the speed of tool rotational, speed of welding and force of axial have 67.31, 13.7 and 14.5 % contribution, respectively. Kulekci [8] used friction stir spot welding to joint aluminum alloy plates (EN AW5005) with a thickness of 1.5 mm with using tool of hardness 52 HRC. They used different parameters of tool rotation (1500 and 2000 rpm), dwell time (5 and 10 s) and the tool pin height (2.2 and 2.6 mm). They found that the increase in tool rotation speed increases the tensile shear strength in a limited range of “FSSW joints” and the increase in the tool pin height increases the tensile shear strength. Effect of tool pin height on the tensile shear strength was greater than dwelling time and tool rotation.

Vanita and Kadlag [9] applied friction stir welding successfully for AA6082-T6 aluminum alloy sheet of 6.5 mm thickness by CNC milling machine. Taper cylindrical tool with three flutes gave the best weld joint among other tools which made of “HSS” for the friction stir welding. Experiments were conducted by varying rotational speed, transverse speed and constant welding depth using “L9 orthogonal array” of “Taguchi method.” This work aims at optimizing process parameters to achieve high tensile strength. They found that the optimum process parameters are 1400 rpm of rotational speed, 20 mm/min of traverse speed and 5 mm of welding depth (constant), respectively, which was leading to higher tensile strength.

Abbass et al. [10] performed friction stir spot welding (FSSW) of an aluminum alloy AA2024T3 sheet to commercial pure copper sheet of 2 mm thick at different tool rotational speeds (800, 1000 and 1250 rpm), plunging times (30, 60 and 90 s) and tool pin profile or geometry (Threaded cylindrical with flute, Tapered cylindrical and straight cylindrical). Process parameters were optimized by using Taguchi

technique and depending on design of experiment (DOE). They found that maximum shear force was obtained at optimum welding parameters: 1250 rpm rotation speed, 90 s plunging time and straight cylindrical pin profile which are obtained from the analysis of response optimizer. Pareto chart the standardized effects of tensile shear results showed that the plunging time was the most effective parameter than other welding parameters (rotation speed and pin profile).

From literature reviews as mentioned above, very limited researches or studies focused about the FSSW process of different Al-alloys (heat treatable with non-heat treatable); therefore, in this work more details are presented. The objective of this work is to optimize the FSSW parameters depending on mechanical properties (tensile shear force and microhardness) of spot welded joints by using Taguchi technique and depending on design of experiment of dissimilar aluminum alloys (AA2024-T3 and AA 5754-H114).

2 Experimental Work

2.1 Materials Used

In this study, 2-mm-thick aluminum alloys AA2024-T3 and AA57454-H114 were used as base materials. Chemical composition analysis of alloys was done using spectrometer instrument ARL in COSQC laborites as shown in Table 1. Tensile test was carried out to determine the mechanical properties of base metals according to ASTM standard E8M –09 for sub-size specimen as shown in Table 2.

2.2 FSSW Procedure

FSSW process was performed by using vertical universal milling machine type (DECKEL FP4MNC-Germany) to fabricate overlap welded joints where the AA2024T3 sheet was upper sheet and AA5754-H114 was lower sheet. Additionally, proper backing sheets were used to obtain the desired lap spot joints. The work pieces have a $25 \times 25 \text{ mm}^2$ overlap area. During FSSW, the friction between the shoulder pin and

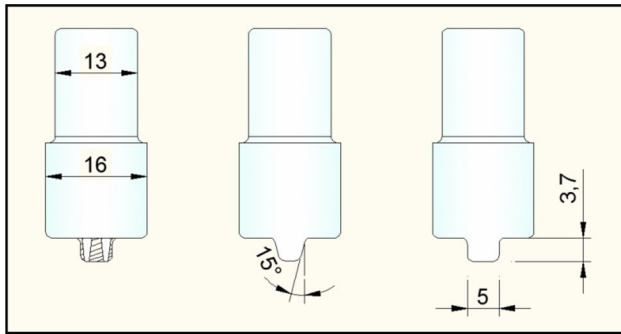


Fig. 1 FSSW tool profile and pin size used in this study **a** Threaded cylindrical with flute (ThC), **b** Tapered cylindrical (TC), straight cylindrical (SC)

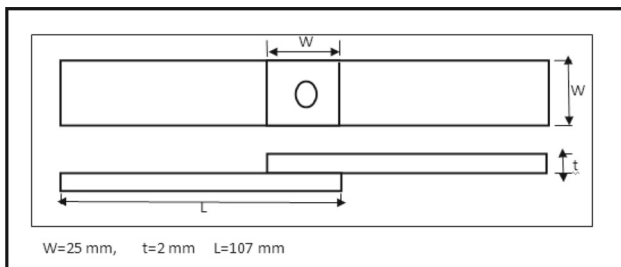


Fig. 2 The design and dimensions of overlap work pieces to be spot welded

the work pieces generates most of the heat energy for joining. The tools used in welding operations were machined from high speed tool steel which has hardness of 54 HRC. Three tools pin profiles (threaded cylindrical with flute, tapered cylindrical and straight cylindrical) were used to fabricate the joints in this study as shown in Fig. 1. The alignment and dimensions of overlap work pieces to be spot welded indicated in Fig. 2. The friction stir spot welding (FSSW) process consists of three stages or steps: plunging, stirring and retracting (drawing out) as shown in Fig. 3 [5].

2.3 Tensile Shear Test

Tensile shear strength was performed on a spot welded specimen with 189 mm length, 25 mm width and 2 mm thick. Welded lap shear specimens were tested on an Instron machine, TGM—France machine Model (03M3818.1) at a constant crosshead speed of 5 mm/min with maximum load 100 KN. For lap shear tensile test, the spot welded specimens of dissimilar metals (Al2024-T3 and AA5754-H114) were gripped with using shims of thickness equal to that of the specimens. The maximum shear load was recoded at fracture point during the test for each FSSW specimen.

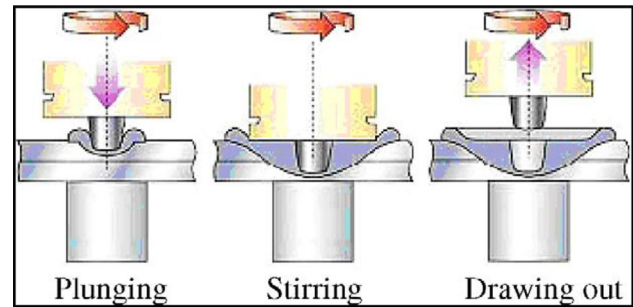


Fig. 3 Schematic illustration steps of friction stir spot welding process [5]

2.4 Microstructure Examination

Microstructure examination was carried out on cross section of spot welded specimen of dissimilar and base alloys using optical microscope type (OPTIKA-ITALY) provided with computer. A specimen preparation was made including wet grinding process with using SiC paper in different grits of 320, 500, 800, 1000, 1200 and 2000, and then polishing process was performed with using 10 μ m diamond past and lubricant and then alumina solution with 3.0 μ m with special cloth to obtain polished surface. To examine the microstructure of specimen, etching process was done using etching solution which consists of (1 ml HF + 99 ml distilled water) for two Al-alloys. Macrostructure of cross section was obtained to study welding zones of joint at optimum welding conditions.

2.5 Hardness Test

Vickers hardness test was performed on the cross section of the spot welded sample, with applied load of 200 g for 15 s by using Vickers hardness device. Microhardness was carried out in nugget (stir) zone, TMAZ, HAZ, hook zone and base metals of AA2024T3 and AA5754-H114, and 12 readings of HV values were taken in each sample to have more accuracy.

3 Results and Discussion

3.1 Tensile Shear Results

Table 3 shows the shear force for specimens of friction stir spot welded formed from AA2024-T3 to AA5754-H114. The maximum shear force is found for specimen No. 8 with values of (2870 N). However, the minimum shear force is found in specimen No. 5 with a value (490 N).

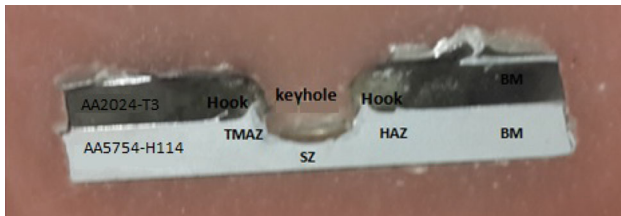
3.2 Macro- and Microstructure Examination

Macro- and microstructural examinations were achieved to investigate the welding characteristics. Due to high pressure



Table 3 Tensile shear force values (AA2024-T3 to AA5754-H114)

Experiment No.	N (rpm)	t (s)	PF	Tensile shear force (Mean) N
1	800	30	SC	960
2	800	60	TC	2860
3	800	90	ThC	660
4	1000	30	TC	1780
5	1000	60	ThC	490
6	1000	90	SC	2630
7	1250	30	ThC	1130
8	1250	60	SC	2840
9	1250	90	TC	1970

**Fig. 4** Macrostructure of the cross section of the spot joint of (AA2024-T3 to AA5754-H114)

and large plastic deformation, the upper and the lower sheets are compressed together to form an effective joint.

Figure 4 shows macrostructure of the cross section of the spot joint (FSSW) of (AA2024-T3 to AA5754-H114) which was welded at best welding parameters. It was seen there are five zones that have different characteristics including the base Metal (BM), the heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), the stir zone (SZ) and the hook on both sides of spot joint. The hooks formed due to the shearing action, and this action propagates to a depth inversely proportional to the yield strength of the welded materials.

The hook is a characteristic feature of friction stir spot welds in lap configuration where there is a formation of a

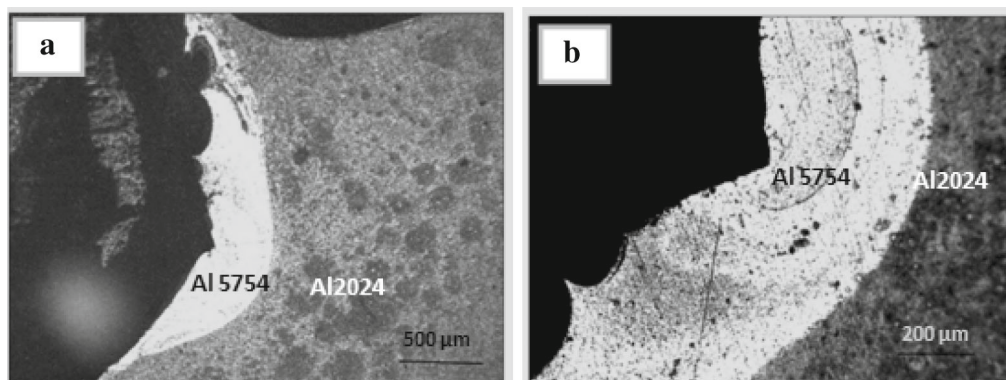
geometrical defect originating at the interface of the two welded sheets [11]. Figure 5 shows the microstructures of the cross section of FSSW joint of (AA2024T3 to AA5754-H114) which was welded at best welding parameters.

3.3 Hook Characteristics

The plastic flow of upper and lower sheets during the spot welding process leads to hooks formation. The high pressure exerted by the rotation pin in addition to the high temperature resulted from friction between the rotating pin and the upper sheet. All these factors resulted in plastic flow of the matting sheets, because the flow of sheet material is constrained by the setup of the proposed tool. So the sheets forced to flow to the weaker place, which is in this case the lower sheet (AA5754-H114), because this sheet is softened more than the upper sheet (AA2024T3), so that all the hooks in this spot welding process are directed upward to the upper sheet as shown in Fig. 6.

3.4 Hardness Results

Figure 7 shows the Vickers hardness profile across section of spot weld of (AA2024-T3 to AA5754-H114) at 12 dif-

**Fig. 5** The microstructures of the cross section of FSSW joint of (AA2024T3 to AA5754-H114). **a)** At ×100, **b)** at ×400

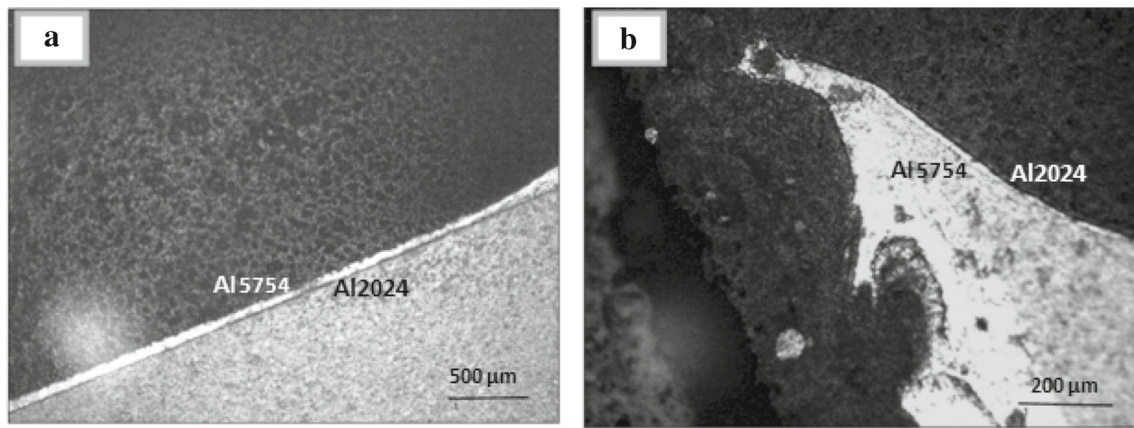


Fig. 6 Interface between the two Al-alloys and hook in spot joint of (AA2024T3 to AA5754-H114). **a** At $\times 100$, **b** at $\times 400$

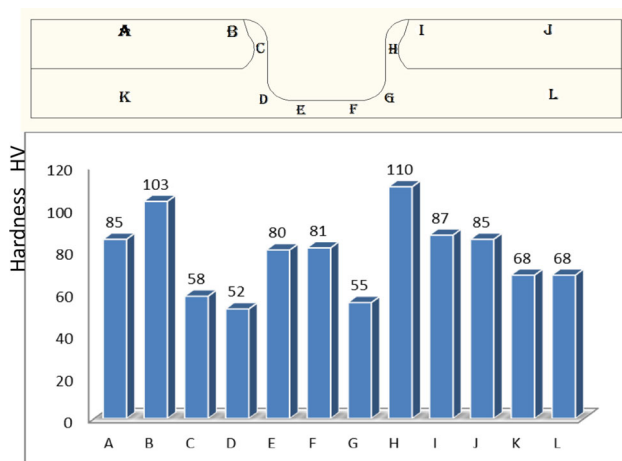


Fig. 7 Hardness Vickers values of (AA2024-T3 to AA5754-H114)

ferent locations of the base metals and HAZ, TMAZ and SZ. The hardness of the stir zone or weld is lower than that of the BM of AA2024-T3. Vickers hardness reduces

gradually in the location of HAZ toward the keyhole, reaching the minimum value of 80 HV in the periphery of the HAZ and TMAZ. The hardness increases dramatically in TMAZ and SZ, however, which is still lower than that of the BM of AA2024, while in hook the hardness reaches a maximum value of 110 HV. Different values of Vickers hardness in each region of the weld can be attributed to the comprehensive effects of the strain-hardening, the dissolution of strengthening phase and the variations in the grain sizes.

From XRD analysis inspection the obtained results demonstrated the formation of intermetallic compounds in the interface between the dissimilar aluminum alloys joints. These intermetallic compounds were revealed as Al_3Mg_2 and Mg_2Si formed on the AA5754-H114 substrate and CuAl , Al_2Cu , AlCu_4 , Cu_9Al_4 formed on the Al2024T3 substrate as shown in Fig. 8. These hardening phases lead to higher hardness of AA2024T3 base alloy than that of AA5754-H114 base alloy.

Fig. 8 XRD pattern results of Al2024T3 alloy

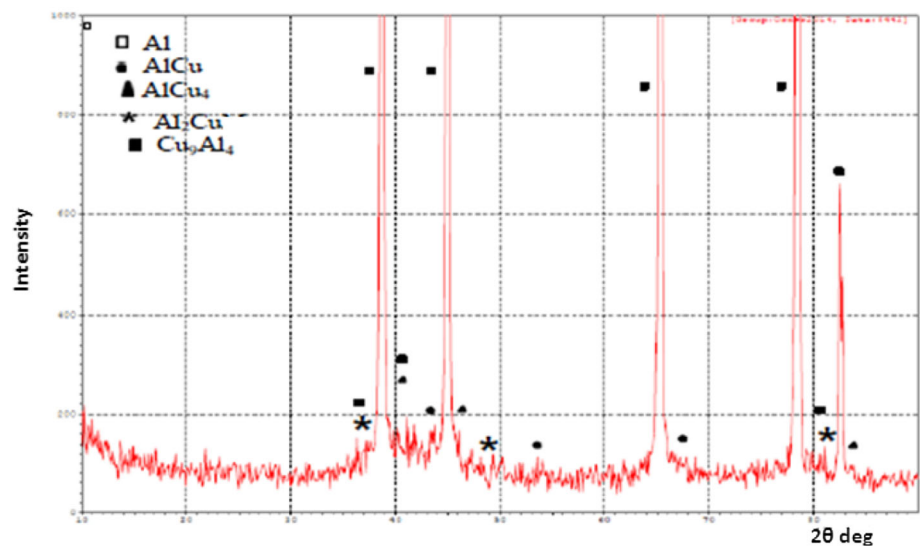
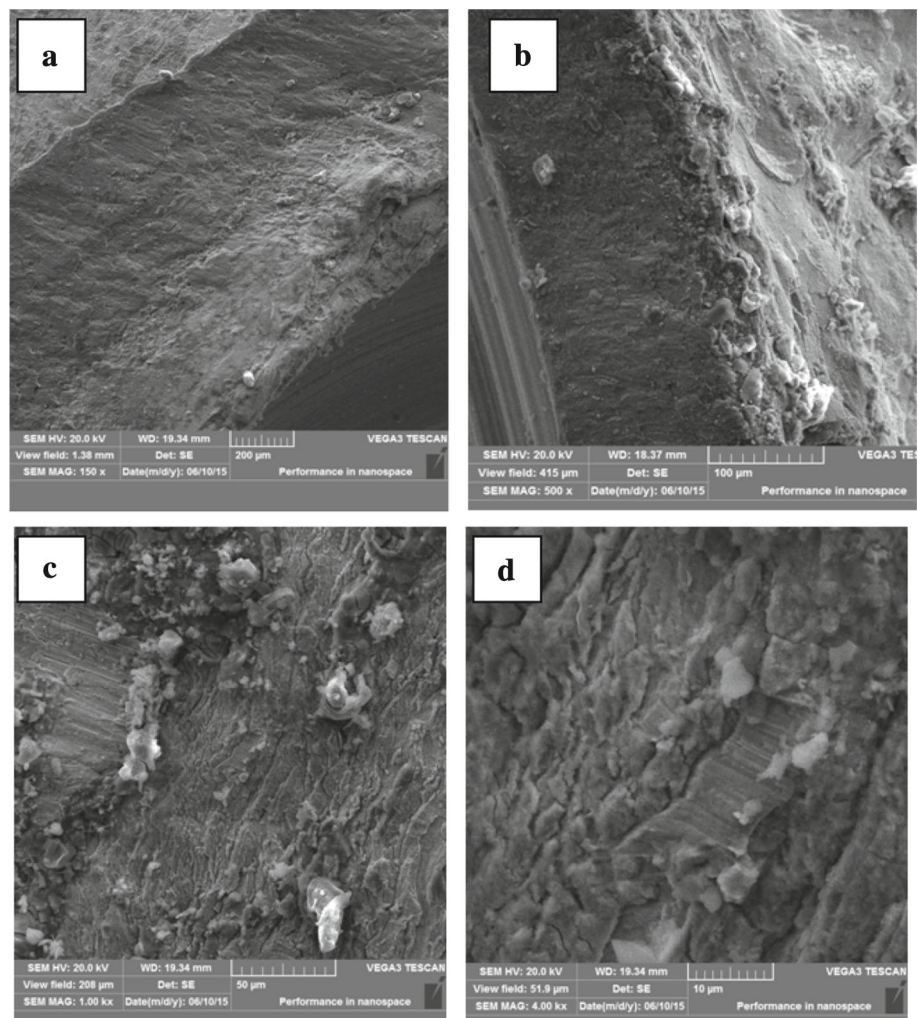


Fig. 9 SEM micrographs of fracture surface on the failed tensile shear sample of the lower sheet for FSSW joint of (AA2024T3 to AA5754-H114)



3.5 Fracture Surfaces

Scanning electron microscope (SEM) was used to characterize the fracture surfaces and determine the failure modes of tensile shear specimens after shear test. In this work, the spot welded specimens have fracture surfaces in lower sheet of type the nugget pull-out separation, two sheets tended to get separated at the bonding zone under loading as shown in Fig. 9a, b. It was seen that fracture surface around nugget zone has two modes of separation, partially shear appearance and partially brittle fracture. This separation led to the formation of an annular crack surrounding the SZ, which resulted in the decrease of effective shear area of the joint. It was indicated that circumferential cracks would nucleate on just one or both sheets. Figure 9c, d shows SEM micrographs of the fracture surface on lower sheet of FSSW joint of (AA2024-T3 to AA5754-H114). The fracture regions were detected near the nugget for FSSW joint, the interface between the nugget and the thermo mechanically affected zone. It was seen the fracture mode was partially brittle and intergranular

cracking in TMAZ due to formation intermetallic compounds and precipitates particles in weld zone. These results are in agreement with those of researcher Shen et al. [12].

3.6 Design of Experiment (DOE) Results

Optimization of process parameters can improve quality and the optimal process parameters obtained from the Taguchi method and other noise factors. Taguchi method is experimental design easy to apply for many engineering applications [13].

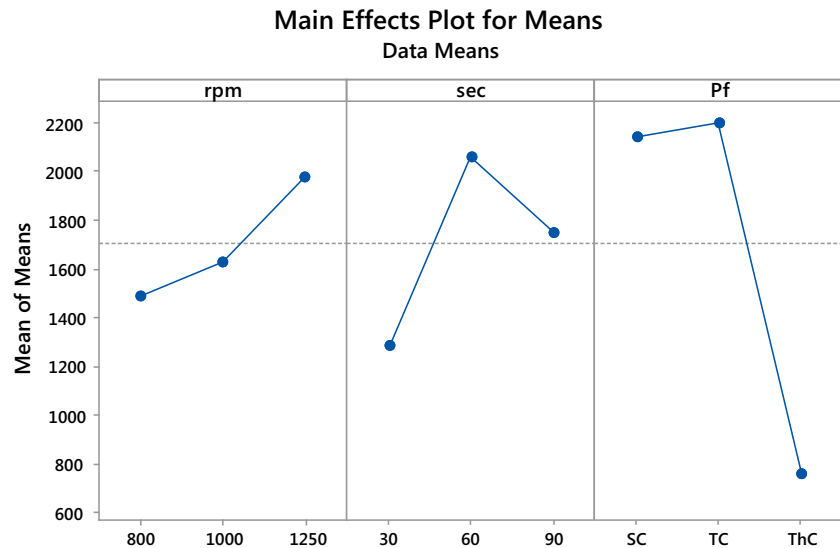
In this work, data analysis based on the Taguchi method (L9 orthogonal array) is performed by utilizing the Minitab 17 to estimate the significant factors of the friction stir spot welding (FSSW) and main effects using few experimental tests only.

3.6.1 Main Effects Plot for Means

Three experiments in each set of process parameters have been performed on (AA2024T3 and AA5754-H114) sheets.

Table 4 Parameters and their levels of FSSW

Parameter	Level 1	Level 2	Level 3
Rotation speed, RS (rpm)	800	1000	1250
plunging time, PT (s)	30	60	90
pin profile, PF	Straight cylindrical (SC)	Tapered cylindrical (TC)	Threaded cylindrical with flute (ThC)

Fig. 10 Main effects plot for means of shear force for dissimilar welded joints (Al2024-T3 to AA5754-H114)

The three factors used in this experiment are the rotating speed, plunge time and tool pin profile as mentioned above. The three factors and the levels of the process parameters are presented in Table 4, and these parameters are taken based on the previous trials to weld the FSSW of aluminum alloy AA2024T3 to AA2024T3. As mentioned above from Table 3, it was seen that maximum tensile shear force was (2860 N) at the best welding process parameters of rotational speed of (800 rpm), plunging time of (60 s) and taper cylindrical. These results are in agreement with those researchers Vanita and Kadlag [9].

Figure 10 shows the main effects plot for means of shear force for dissimilar welded joints (Al2024T3 to Al5754-H114). It was seen that the tensile shear force reaches a maximum value at the optimum value of process parameters of rotational speed of (1250 rpm) (level 3), plunging time of (60 s) (level 2) and taper cylindrical pin (level 2).

3.6.2 Response Optimizer

This method is used to detect the input variable of the combination settings that jointly optimize a single or a set of responses. In Minitab, the response optimizer can be used to search for optimal (best) responses built on the definite requirements for each response [13]:

- Maximize the response (higher is better, e.g., strength)

- Target the response (target is best, e.g., part dimension)
- Minimize the response (smaller is better, e.g., time)

In this work, the response optimizer method is used to show which factors have on welding parameter separately and their impact on shear force which gives the best value of shear strength. Figure 11 shows response optimizer of dissimilar spot welded joints of dissimilar Al-alloys (AA2024T3 to AA5754-H114). It was found the optimum input parameter for friction stir spot welding joints are rotational speed 1250 rpm, plunging time 90 min and straight cylindrical pin profile and constant dwell time 10 s and plunge depth (3.8 mm).

3.6.3 Pareto Chart Results

Pareto charts are useful and helpful method for analyzing that parameters or variables requiring interest primarily since the longer bars at the chart clearly show that the variables have the most significant effect on a given system [14]. The chart represents the absolute value to the effects and draws line as the reference at the chart. The method Minitab uses to draw Pareto chart of the effects depend on the freedom degrees for the term of error. Figure 12 represents Pareto chart of the standardized effects of tensile shear results (in case of effect single factor), and it was noticed that the tool pin profile (factor C) is the most effective parameter as compared to others (factors A and B). Also it was found that the contribu-



Fig. 11 Response optimizer of dissimilar spot welded joints of (AA2024-T3 to AA5754-H114)

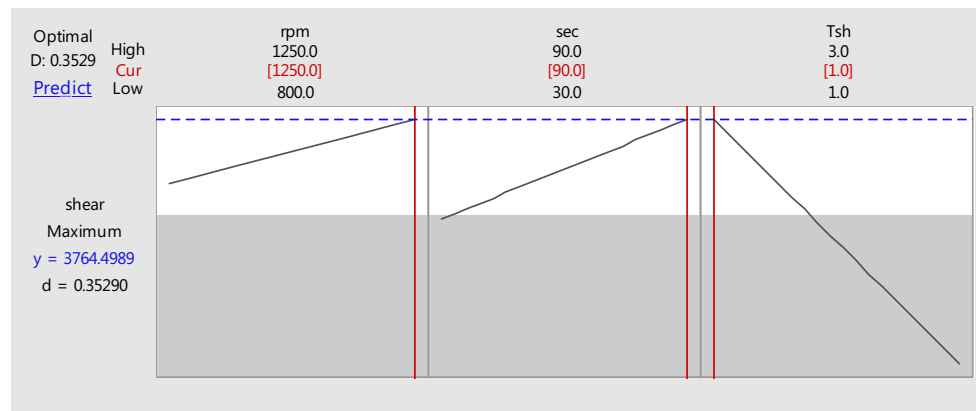


Fig. 12 Effect of welding parameters on shear force (single factor)

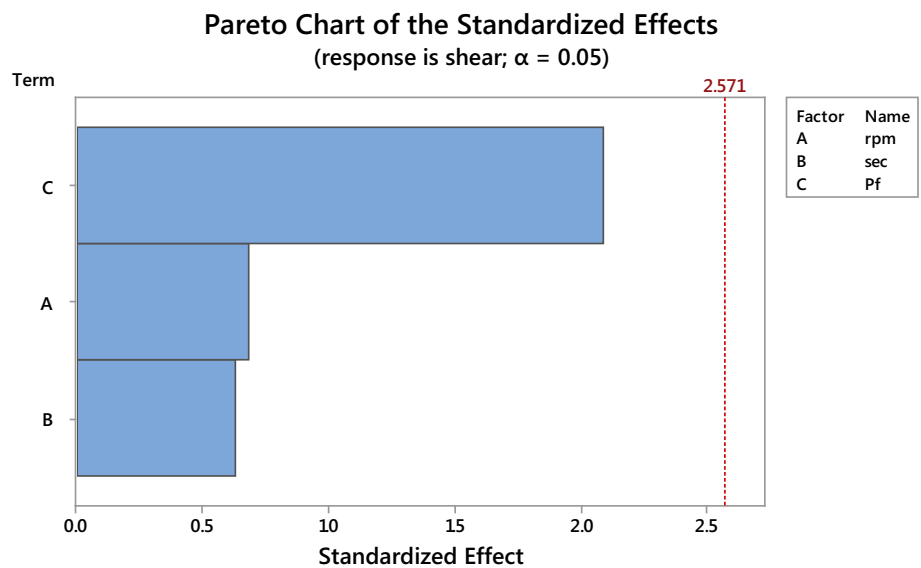
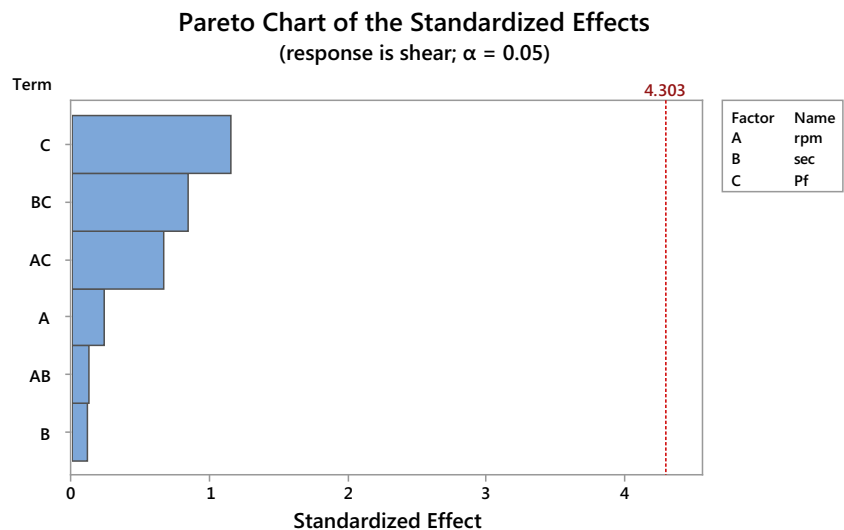


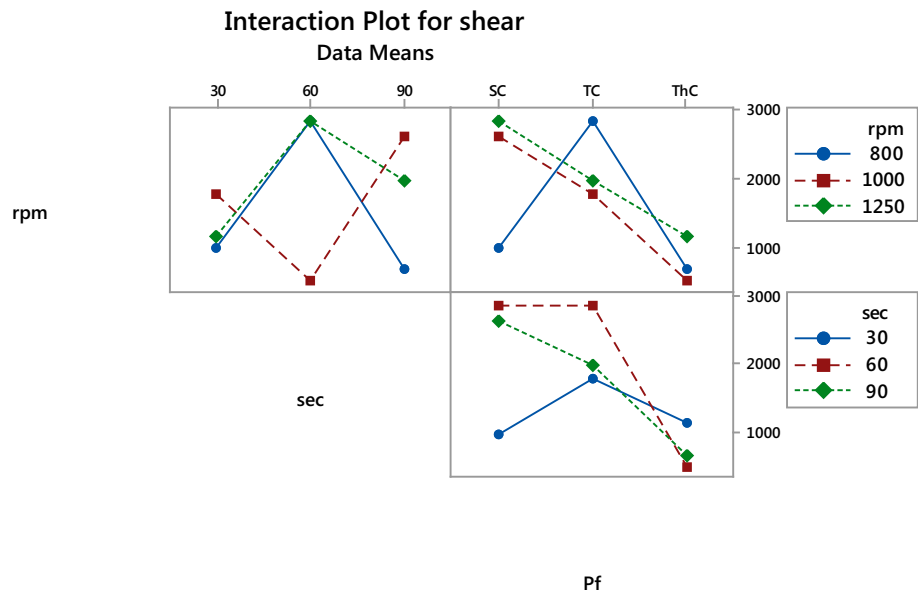
Fig. 13 Effect of welding parameters on shear force (combined two factors)



tion percentage was 61.5 % for pin profile followed by tool rotation speed 20.1 % and plunging time 18.4 %. In case of effect combined two factors, Pareto chart of the standardized effects of tensile shear results showed that the plunging time

and tool pin profile (factor BC) were more effect parameter than others (factors AC and AB) which are $C = 36.75\%$, $BC = 27.2\%$, $AC = 21.1\%$, $A = 7.58\%$, $AB = 3.92\%$ and $B = 3.45\%$ as shown in Fig. 13.

Fig. 14 Interaction plot of shear force of dissimilar spot welded (AA2024-T3 to AA5754-H114)



The interaction plot represents the effect of one factor on the others to give the behavior of response. Figure 14 shows the effect of all FSSW parameters on tensile shear force of dissimilar spot joint of (AA2024-T3 to AA5754-H114).

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4 Conclusions

1. It was found from experiment work that tensile shear force increases with increasing plunging time up to (60 s) specific limit and then decreases, while the shear force increases with increasing tool rotation speed at same tool pin profile.
2. The optimum value of welding parameters of rotational speed, plunging time and tool pin profile were found to be 1250 rpm, 60 min and taper cylindrical pin, respectively, which are obtained from the analysis of response optimizer.
3. It was noticed that the tool pin profile is the most effective parameter as compared to others; also it was found that the contribution percentage was 61.5 % for pin profile followed by tool rotation speed 20.1 % and plunging time 18.4 %.
4. Hardness profile of the lap spot dissimilar joints of AA2024 to AA5754 exhibited the lower hardness values that appeared in the TMAZ and HAZ because of characteristic of intermetallic compounds Mg_2Si and Al_3Mg_2 and precipitates of $AlCu$, Al_2Cu , Al_9Cu_4 which were detected by XRD analysis inspection.

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